

^{26}Al yields from rotating Wolf–Rayet star models

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Abstract

We present new ^{26}Al stellar yields from rotating Wolf–Rayet stellar models which, at solar metallicity, well reproduce the observed properties of the Wolf-Rayet populations. These new yields are enhanced with respect to non-rotating models, even with respect to non-rotating models computed with enhanced mass loss rates. We briefly discuss some implications of the use of these new yields for estimating the global contribution of Wolf-Rayet stars to the quantity of ^{26}Al now present in the Milky Way.

Key words: γ -ray astronomy; Wolf–Rayet stars; nucleosynthesis

1 Introduction

Many papers, in the past, have explored the possibility that Wolf-Rayet stars, through their winds, might enrich the interstellar medium in ^{26}Al . The idea was first suggested by Dearborn and Blake (1) and was further explored by many

authors (see the review by Prantzos and Diehl (8) and references therein). These computations showed that indeed Wolf-Rayet stars appear to be significant ^{26}Al sources. It is the hope that in the future, γ -ray astronomy, by measuring the 1.8 MeV luminosity of single objects, will be able to add new constraints on the stellar models and thus clearly identify the source of this element in the Galaxy. An upper limit for the 1.8 MeV luminosity exists only in the case of $\gamma^2\text{Vel}$, the nearest known WR star (Oberlack et al. (6)). All the other constraints concern either the Galaxy as a whole or directions in the Galaxy with *gamma*-ray line luminosities arising from the cumulative effects of different populations whose relative contributions are still difficult to assess. There is however a few very young associations or groups of associations which are too young for having been much enriched by the supernovae. In those cases, a significant part of the 1.8 MeV luminosity likely originates from the decay of ^{26}Al ejected by the winds of Wolf-Rayet (WR) stars. These regions are thus particularly interesting as they offer a unique probe of one single type of sources (Knödlseeder et al. (2); Plüschke et al. (7)).

A striking conclusion of the work by Knödlseeder et al. (2) who studied the Cygnus associations, is that the theoretical ^{26}Al yields seem to be underestimated by a factor of two. At first sight, this conclusion is surprising because the WR yields are based on models computed with enhanced, (nowadays considered to be overestimated) mass loss rates (Meynet et al. (5)). One would have thus expected that the too strong mass loss suffered by these models would give too high ^{26}Al yields ! On the other hand, despite the uncertainties pertaining to the mass loss rates, there was good hope that the yields of these models would not be too far from reality in the sense that the enhanced mass loss rate models were able to account for many observable properties of WR stars as for instance the number ratio of WR to O type stars in zones of constant star formation rate (Maeder & Meynet (3)).

Recently, a new grid of WR stellar models at solar metallicity has been computed accounting for the effects of rotation and including new prescriptions for the mass loss rates. The new revised mass loss rates include the effects due to clumping in WR stellar winds and are about a factor two to three below those used in the enhanced mass loss rate models. Interestingly, despite using much lower mass loss rates, the rotating models can explain the observed number ratio of WR to O-type stars at solar metallicity. They can even reproduce the observed fraction of WR stars presenting at their surface both H and He-burning products, an observational fact which non-rotating models could not explain (with normal or enhanced mass loss rates). Finally they also well match the number ratio of WC to WN stars. Thus it appears that the necessity to enhance the mass loss rate in the old models was probably due to the neglect of rotation.

The aim of this paper is to study the yields in ^{26}Al derived from these new

rotating models (only the wind contribution is considered here).

2 Effects of rotation on the ^{26}Al yields from WR stars

The physical ingredients of these models are exactly the same as in the models by Meynet & Maeder (4), except for one thing: we did not take into account the effects of the wind anisotropies induced by rotation. This is quite justified since it has been shown in the above reference that for the initial velocities considered here the effects are negligible. We consider here an initial equatorial rotation velocity on the ZAMS of 300 km s^{-1} . This corresponds to a time averaged equatorial velocity during the Main Sequence phase of about 200 km s^{-1} , a typical value for this kind of star. Figure 1 presents the evolution of the structure of four $60 M_{\odot}$ stellar models with different metallicities and initial rotational velocities. The evolutions of the central and surface abundances of ^{26}Al are also indicated. Comparing the non-rotating models with the rotating ones, one can note two striking differences:

- As a result of rotational mixing the convective core in the rotating model is continuously supplied with fuel and CNO elements which act as catalysts of the H-burning reactions. Therefore, the decrease in mass of the convective core is slowed down and the lifetime on the Main Sequence is enhanced. This feature is more marked in the higher metallicity model, in which the greater CNO content reinforces the process just described above. This effect of rotation tends to favour ^{26}Al production by WR stars. Indeed more extended convective cores reduce the extension of the region separating the core, where ^{26}Al is produced, from the surface, where it is ejected into the interstellar medium by stellar winds.
- In the non-rotating models, the abundance in ^{26}Al begins to increase at the surface when layers having been processed in the convective core appear at the surface as a result of mass loss. In the rotating model, the enrichment in ^{26}Al of the surface occurs at a much earlier stage when the core is still surrounded by an important H-rich envelope. This may happen thanks to rotational mixing which brings up to the surface matter processed in the core. Thus the wind becomes ^{26}Al enriched at a much earlier stage than in the non-rotating models and the total quantity of ejected ^{26}Al increases.

In addition to these two effects which are well apparent in Fig. 1, at least two other effects contribute to enhance the ^{26}Al yields in rotating models: 1) some amounts of ^{25}Mg diffuse from the radiative envelope in the central H-burning regions where it is transformed by proton capture in ^{26}Al , 2) the minimum initial mass of single stars passing through a WR episode is decreased. For all these reasons, the yields of the rotating models are enhanced with respect to those of non-rotating models computed with exactly the same physical

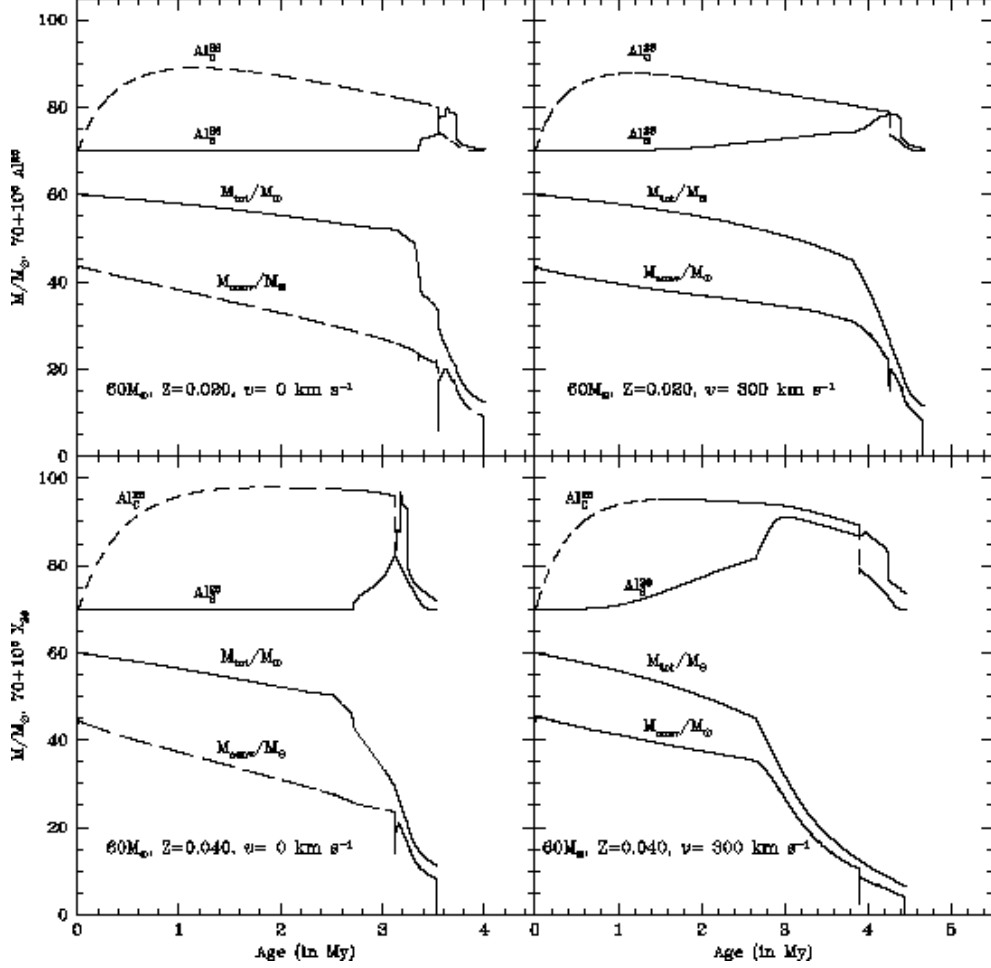


Fig. 1. Evolution as a function of time of the surface and central abundance of ^{26}Al in mass fraction (labeled respectively by Al_S^{26} and Al_C^{26}), of the total mass and of the mass of the convective core in four $60 M_\odot$ stellar models. The initial metallicities and rotational velocities are indicated on each panel.

ingredients. The enhancement factors are slightly superior to 2 for the 60 and the $120 M_\odot$ and amounts to 340 in the case of the $25 M_\odot$ stellar model. Note that the non-rotating $25 M_\odot$ never becomes a WR star, while its rotating counterpart goes through a WR phase (hence the huge enhancement factor).

On Fig. 2 the yields from the present rotating models are compared with those obtained from the enhanced mass loss rate models. One sees that the yields obtained in the new rotating models, both at solar metallicity and at twice the solar metallicity, are greater than those of Meynet et al. (5), the increase becoming more and more important when the initial mass decreases. More quantitatively, at solar metallicity, the yields for the rotating 25 , 60 and $120 M_\odot$ stellar models are multiplied by a factor 12.7, 1.5 and 1.1 with respect to the yields of Meynet et al (5) for the same masses. In order to give an idea of the effects of these enhancement factors on the quantity of ^{26}Al ejected by a generation of stars, one can define an average yield, \bar{Y}_{26} , by

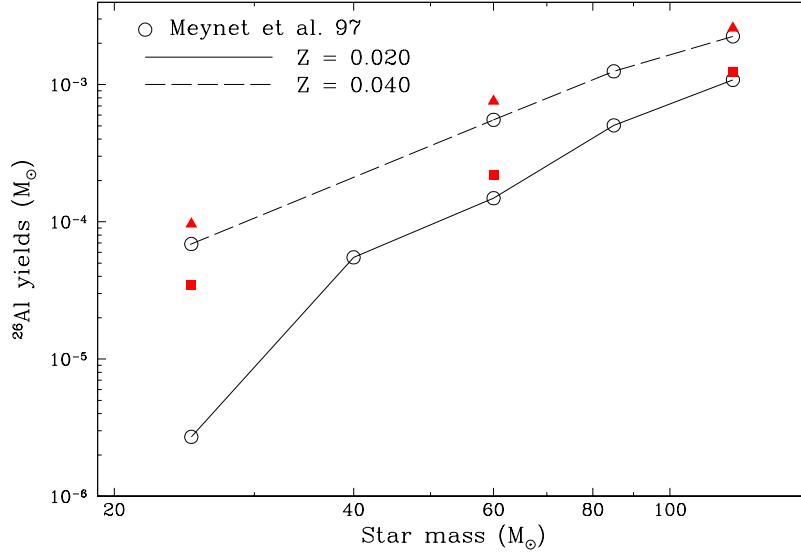


Fig. 2. Comparison of the ^{26}Al yields obtained from the present rotating models, filled symbols, with those of Meynet et al. (5), lines with open circles. Squares show the results for the rotating solar metallicity models, and triangles for the rotating models with twice the solar metallicity.

$$\bar{Y}_{26} = \frac{\int_{M_{\min}}^{M_{\max}} Y_{26}(M) \phi(M) dM}{\int_{M_{\min}}^{M_{\max}} \phi(M) dM}, \text{ where } M_{\min}, M_{\max} \text{ are the lower and upper bound}$$

respectively of the mass range considered, $Y_{26}(M)$ the yield in ^{26}Al of the WR star of initial mass M and $\phi(M)$ the initial mass function (IMF) chosen here with a Salpeter slope (1.35). The value of this average yield computed in the mass range between 25 and 70 M_{\odot} is equal to $5.1 \times 10^{-5} M_{\odot}$ when the stellar yields from the enhanced mass loss rate models are used. Computing the same average yield from the rotating model, one obtains a value of $9.7 \times 10^{-5} M_{\odot}$, nearly twice as great as the one obtained from the enhanced mass loss rate models.

We mentioned above that observations of the Cygnus associations suggest that the theoretical ^{26}Al yields might be underestimated by about a factor two. Indeed, Knödlseider et al. (2) converting the observed 1.8 MeV flux measurements into an equivalent O7V star ^{26}Al yield, obtain a value $Y_{26}^{\text{O7V}} = (1.1 \pm 0.3) \times 10^{-4} M_{\odot}$ for the Cygnus region. This empirical mean yield per equivalent O7V star is about a factor two above the value deduced from their population synthesis model ($Y_{26}^{\text{O7V}} = 4.7 \times 10^{-5} M_{\odot}$) which, on the other hand, very well reproduces the ionizing luminosity of the Cygnus region. How would the use of the present models change the situation? An appropriate quantitative assessment of this point requires a careful study that will be made in a forthcoming paper. Let us simply mention here that if rotation would only affect the ^{26}Al yields, then the above difficulty would be greatly alleviated by the use of the present yields. However, rotation makes also the tracks slightly

bluer and more luminous and thus rotation will also increase the ionising luminosity of the stars. Thus the definite answer to the above question remains largely open as long as no detailed population synthesis models are performed.

What is the fraction of the 2-3 M_{\odot} of ^{26}Al believed to be present in the Milky-Way which has been ejected by the WR stellar winds ? On the basis of the enhanced mass loss rate models the WR contribution was estimated to be between 0.9 and 1.5 M_{\odot} depending on the value of the slope of the IMF (respectively 1.7 and 1.35). First estimates, using the present yields (Meynet et al. in preparation) indicate that the contribution of the WR stars might amount to values between 1.2 (1.7) and 2 M_{\odot} (1.35). Thus, rotation appears to reinforce the WR contribution to the observed ^{26}Al in the Galaxy.

3 Conclusion

From the considerations above, we can retain the following conclusions:

- Rotation increases the contribution of the WR stars to the ^{26}Al synthesis. A significant part of the increase results from the lowering of the minimum initial mass of the stars going through a WR episode.
- The increase of the ^{26}Al yields due to rotation appears to be sufficient for significantly reducing the difficulty encountered in reproducing the 1.8 MeV luminosity of the Cygnus region. However it remains to see if these models can also reproduce the ionising luminosity observed from this region.

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